

Asymmetric dark matter and the Sun

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Cold dark matter particles with an intrinsic matter-antimatter asymmetry do not annihilate after gravitational capture by the Sun and can affect its interior structure. The rate of capture is exponentially enhanced when such particles have self-interactions of the right order to explain structure formation on galactic scales. A ‘dark baryon’ of mass 5 GeV is a natural candidate and has the required relic abundance if its asymmetry is similar to that of ordinary baryons. We show that such particles can solve the ‘solar composition problem’. The predicted small decrease in the low energy neutrino fluxes may be measurable by the Borexino and SNO+ experiments.

We consider the capture by the Sun of asymmetric dark matter (ADM) particles which have a relic asymmetry just as do baryons, in contrast to the usual candidates for cold dark matter (CDM) such as supersymmetric neutralinos which have a relic thermal abundance determined by ‘freeze-out’ from chemical equilibrium. Hence ADM does not annihilate upon capture in astrophysical bodies such as the Sun, leading to a build up of its concentration. In particular, self-interactions can lead to an *exponential* increase of the ADM abundance in the Sun as it orbits around the Galaxy, accreting dark matter.

ADM does not have the usual indirect signatures e.g. there will be no high energy neutrino signal from annihilations in the Sun. Instead ADM will alter heat transport in the solar interior thus affecting the low energy neutrino flux. This had been proposed as a solution to the ‘solar neutrino problem’ [1–3]. Although the solution is now understood to be neutrino oscillations [4], small changes induced by accreted CDM particles may account for the current discrepancy [5] between helioseismological data and the revised ‘Standard Solar Model’ (SSM).

An asymmetry in ADM similar to that in baryons naturally explains why their observed abundances are of the same order of magnitude. If ADM arises from a strongly coupled theory (like the baryon of QCD), then there is a conserved $U(1)$ global symmetry (like B number in QCD) which guarantees stability of the lightest $U(1)$ charged object. Technicolour models of electroweak symmetry breaking [6] provide an example of ADM from strong dynamics in the form of the lightest neutral technibaryon [7]. Recently, new viable types of technibaryon dark matter (TIMPs) [8] as well as other particle candidates for ADM [9] have been suggested.

While gravitational instability in collisionless CDM provides a good explanation for the large-scale structures of the universe, observations on galactic and smaller scales suggest that CDM may be self-interacting [11, 12]. If ADM arises as a composite TIMP or a ‘dark baryon’ from a strongly coupled model, then it would naturally have such self-interactions.

We consider how the capture of self-interacting ADM by the Sun can alter helioseismology and low energy neutrino fluxes.

CAPTURE OF SELF-INTERACTING ADM

We refer to earlier discussions of the capture by the Sun of heavy Dirac neutrinos having an asymmetry [13], and of symmetric CDM with self-interactions [14]. The capture rate for CDM particles χ with *both* an asymmetry and self-interactions is governed by the equation:

$$\frac{dN_\chi}{dt} = C_{\chi N} + C_{\chi\chi}N_\chi. \quad (1)$$

Here $C_{\chi N}$ is the usual rate of capture of CDM particles by scattering off nuclei (mainly protons) within the Sun, while $C_{\chi\chi}$ is the rate of self-capture through scattering off already captured χ particles. Hence the number of captured particles would have grown as

$$N_\chi(t) = \frac{C_{\chi N}}{C_{\chi\chi}} (e^{C_{\chi\chi}t} - 1), \quad (2)$$

i.e. *exponentially* for $t \gtrsim C_{\chi\chi}^{-1}$. However the effective cross-section for self-captures cannot increase beyond πr_χ^2 where r_χ is the scale-height of the region where they are gravitationally trapped [1]. The linear growth by contrast can continue up to the ‘black disk’ limit i.e. πR_\odot^2 . In both cases there is an additional enhancement due to ‘gravitational focussing’ [1, 15] as we quantify later. The ejection of captured ADM particles by recoil effects in the self-scattering can be neglected [14] and evaporation is negligible for a mass exceeding 3.7 GeV [15].

The ADM capture rate through spin-independent (SI) and spin-dependent (SD) interactions can be written [16]:

$$C_{\chi N}^{\text{SI,SD}} = c_{\chi N}^{\text{SI,SD}} \left(\frac{\rho_{\text{local}}}{0.4 \text{ GeV cm}^{-3}} \right) \sum_i \mathcal{F}_i \left(\frac{\sigma_i^{\text{SI,SD}}}{10^{-40} \text{ cm}^2} \right) \quad (3)$$

where $c_{\chi N}^{\text{SI}} = 6.4 \times 10^{24} \text{ s}^{-1}$ and $c_{\chi N}^{\text{SD}} = 1.7 \times 10^{25} \text{ s}^{-1}$, ρ_{local} is the estimated local CDM density, and $\mathcal{F}_i(m_\chi)$ encodes the form factors for different nuclei i weighted by the solar chemical composition — the sum is over all nuclei (hydrogen only for SD interactions). Here $\sigma_{\chi N}^{\text{SI,SD}}$ is the ADM-*nucleus* cross-section, which is related to $\sigma_{\chi N}$, the ADM-nucleon cross-section [16]. For spin-independent interactions, $\sigma_{\chi N}$ is constrained by direct detection experiments such as CDMS-II [17], XENON10 [18] and Co-

GeNT [19] to be $\lesssim 10^{-39} \text{ cm}^2$ for $m_\chi = 5 \text{ GeV}$. For spin-dependent interactions the constraints are considerably weaker, e.g. PICASSO [20] sets the strongest bound of $\lesssim 10^{-36} \text{ cm}^2$ for this mass.

Next we consider the self-capture rate in the Sun [14]:

$$C_{\chi\chi} = \sqrt{\frac{3}{2}} \rho_{\text{local}} s_\chi \frac{v_{\text{esc}}^2(R_\odot)}{\bar{v}} \langle \phi \rangle \frac{\text{erf}(\eta)}{\eta} \quad (4)$$

where $s_\chi \equiv \sigma_{\chi\chi}/m_\chi$ is the ADM self-interaction cross section divided by its mass, and $v_{\text{esc}}(R_\odot) \sim 618 \text{ km s}^{-1}$ is the escape velocity at the surface of the Sun, which is assumed to be moving at $v_\odot = 220 \text{ km s}^{-1}$ through a Maxwell-Boltzmann distribution of CDM particles with velocity dispersion, $\bar{v} \sim 270 \text{ km s}^{-1}$. Here $\langle \phi \rangle \sim 5.1$ is the average over $\phi(r) \equiv v_{\text{esc}}^2(r)/v_{\text{esc}}^2(R)$ and $\eta \equiv \sqrt{3/2} v_\odot/\bar{v}$.

Self-interacting CDM was proposed [11] to account for observations of galactic and subgalactic structure on scales \lesssim a few Mpc which are not in accord with numerical simulations using collisionless cold particles. The discrepancy can be solved if CDM has a mean free path against self-interactions of $\lambda \sim 1 \text{ kpc} - 1 \text{ Mpc}$ corresponding to a self-scattering cross-section between $s_\chi \sim 8 \times 10^{-22}$ and $\sim 8 \times 10^{-25} \text{ cm}^2 \text{ GeV}^{-1}$ [11]. A detailed analysis sets an upper limit of $s_\chi \lesssim 10^{-23} \text{ cm}^2 \text{ GeV}^{-1}$ [12], while a study [21] of the colliding ‘Bullet cluster’ of galaxies implies a stronger bound of $\sim 2 \times 10^{-24} \text{ cm}^2 \text{ GeV}^{-1}$, which we adopt for our calculations below.

A ‘dark baryon’ from a QCD-like strongly interacting sector but with a mass of about 5 GeV is a natural candidate for ADM. Its relic density is linked to the relic density of baryons via $\Omega_\chi \sim (m_\chi \mathcal{N}_\chi / m_B \mathcal{N}_B) \Omega_B$ where $\mathcal{N}_{B,\chi}$ are the respective asymmetries. If $\mathcal{N}_B \sim \mathcal{N}_\chi$ (e.g. if both asymmetries are created by ‘leptogenesis’ [22]) then the required CDM abundance is realised naturally. The self-interaction cross-section of such a neutral particle can be estimated by scaling up the neutron self-scattering cross-section $\sim 10^{-23} \text{ cm}^2$ [23] as: $\sigma_{\chi\chi} = (m_n/m_\chi)^2 \sigma_{nn}$ which is just of the required order. Note that the self-annihilation cross-section will be of the same order which ensures that the ADM thermal (*symmetric*) relic abundance is negligible, just as it is for baryons.

Photon exchange, via a magnetic moment of the dark baryon, will give rise to both spin-independent and spin-dependent interactions of χ with nucleons. Recently this has been investigated in a model of a 5 GeV dark baryon in a ‘hidden sector’ interacting with the photon through mixing with a hidden photon magnetic moment [10]. From this model we infer that spin-independent cross-section with nuclei of $\mathcal{O}(10^{-39}) \text{ cm}^2$ can be achieved. Moreover this will be accompanied by spin-dependent interactions which would aid further in the heat transport in the Sun as discussed below. Since the photon couples *only* to the proton in direct detection experiments, the limit on $\sigma_{\chi N}$ is degraded for this model to $\sim 4 \times 10^{-39} \text{ cm}^2$ which we adopt as an example later.

HELIOSEISMOLOGY AND SOLAR NEUTRINOS

Fig. 1 shows the growth of the number of captured ADM particles in ratio to the number of baryons in the Sun, for a scattering cross-section on nucleons as large as is experimentally allowed, including the ‘gravitational focussing’ factor of $(v_{\text{esc}}(r)/\bar{v})^2$ [15] and setting $r = R_\odot$ or $r_\chi (\simeq 0.07 R_\odot$ for $m_\chi = 5 \text{ GeV}$) as appropriate.

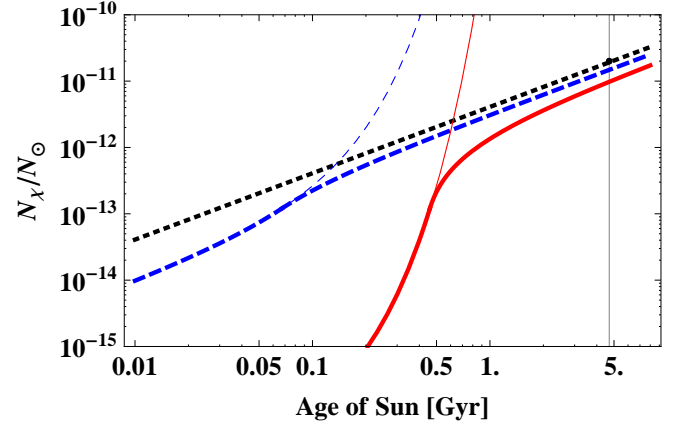


FIG. 1: Growth of the relative abundance of 5 GeV mass ADM particles in the Sun until its present age (vertical line) assuming $s_{\chi\chi} = 2 \times 10^{-24} \text{ cm}^2 \text{ GeV}^{-1}$, and $\sigma_{\chi N} = 10^{-39} \text{ cm}^2$ (solid line) and 10^{-36} cm^2 (dashed line), these being the maximum experimentally allowed values for spin-independent and spin-dependent interactions respectively. Also shown is the ‘black disk’ limit (dotted line) for the Sun.

Note that due to the self-captures, the limiting abundance $N_\chi/N_\odot \sim 2 \times 10^{-11}$ is almost independent of the actual scattering cross-section. Such an ADM fraction in the Sun can affect the thermal conductivity and thereby solar neutrino fluxes [1, 2]. The SSM [24] predicts 3 times the observed neutrino flux (the ‘Solar neutrino problem’) but this is now well understood taking into account neutrino oscillations [4]. Moreover until recently, the SSM with the ‘standard’ solar composition [25] agreed very well with helioseismology [26]. However the revision of the solar composition [27] means that the SSM no longer reproduces the sound speed and density profile so there is now a ‘solar composition problem’ [5]. We show that the presence of ADM in the Sun can resolve this problem and precision measurements of solar neutrino fluxes can constrain the properties of self-interacting ADM.

A simple scaling argument gives for the luminosity carried by the ADM [1]:

$$L_\chi \sim 4 \times 10^{12} L_\odot \frac{N_\chi}{N_\odot} \frac{\sigma_{\chi N}}{\sigma_\odot} \sqrt{\frac{m_N}{m_\chi}}, \quad (5)$$

where $L_\odot \sim 4 \times 10^{33} \text{ erg s}^{-1}$. When the ADM mean free path λ_χ is large compared to the scale-height r_χ then the energy transfer is *non-local*. This is the case when

$\sigma_{\chi N} \ll \sigma_{\odot}$ where $\sigma_{\odot} \equiv (m_N/M_{\odot})R_{\odot}^2 \sim 4 \times 10^{-36} \text{ cm}^2$ is a critical scattering cross-section. We consider the ADM trapped in the Sun as an isothermal gas at temperature T_{χ} [1], so the luminosity L_{χ} carried by the particles is:

$$L_{\chi}(r) = \int_0^r dr' 4\pi r'^2 \rho(r') \epsilon_{\chi}(r'), \quad (6)$$

where $\epsilon_{\chi}(r') \propto (T(r') - T_{\chi})N_{\chi}\sigma_{\chi N}$ is the energy transferred to the ADM per second per gram of nuclear matter and $\rho(r')$ is the density in the Sun [1]. The ADM temperature T_{χ} is fixed by requiring that the energy absorbed in the inner region ($T(r) > T_{\chi}$) is equal to that released in the outer region ($T(r) < T_{\chi}$), such that $L_{\chi}(R_{\odot}) = 0$.

This approximation overestimates the energy transfer by a small factor [28, 29] but is sufficiently accurate for the present study. We adopt a simple polytropic model for the Sun's temperature T , number density n_p and gravitational potential V [1]. The resulting variation of the solar luminosity $\delta L(r) \equiv L_{\chi}(r)/L_{\odot}(r)$ is shown in Fig. 2 assuming $\sigma_{\chi N} = 4 \times 10^{-39} \text{ cm}^2$ (i.e. $10^{-3}\sigma_{\odot}$) and $N_{\chi} = 2 \times 10^{-11}N_{\odot}$ from Fig 1. Note that the luminosity scales linearly with both $\sigma_{\chi N}$ and N_{χ}/N_{\odot} .

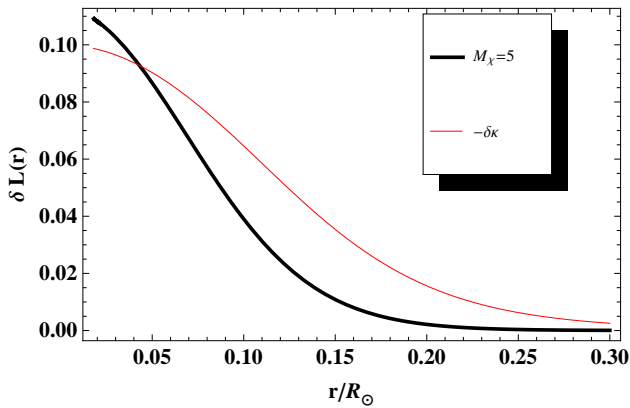


FIG. 2: The radial variation of $\delta L(r) \equiv L_{\chi}(r)/L_{\odot}(r)$ due to ADM of mass 5 GeV, using the approximation of Ref.[1] and $L_{\odot}(r)$ from the BS05 (OP) Standard Solar Model [24].

From the radiative transport equation it follows that a small variation of the solar luminosity is equivalent to an *opposite* small variation in the effective radiative opacity: $\delta L(r) \sim -\delta\kappa_{\gamma}(r) \equiv -\kappa_{\chi}(r)/\kappa_{\gamma}(r)$ [30]. The effect of such a localised opacity variation in the region $r \lesssim 0.2R_{\odot}$ has been studied by a Monte Carlo simulation [31] and results in excellent agreement obtained using a linear approximation to the solar structure equations [32]. Fig. 2 shows that the opacity modification due to a 5 GeV ADM with a relative concentration of 10^{-11} is roughly equivalent to the effect of a 10% opacity variation. The impact of this luminosity variation on neutrino fluxes can be estimated by evaluating $\delta L(r)$ at the scale height of the ADM distribution, $\delta L(r_{\chi})$ [11]. In general, to have an observable effect requires $\sigma_{\chi N}N_{\chi}/\sigma_{\odot}N_{\odot} \gtrsim 10^{-14}$.

It is possible through helioseismology to determine e.g. the mean variations of the sound speed profile $\langle \delta c/c \rangle$ and density $\langle \delta \rho/\rho \rangle$ of the Sun, as well as the boundary of the convective zone R_{CZ} . In particular R_{CZ} is determined to be $(0.713 \pm 0.001)R_{\odot}$ while the SSM with the revised composition [27] predicts values that are too high by up to 15σ [26]. Lowering the opacity in the central region of the Sun with ADM also lowers the convective boundary. The 10% opacity variation shown in Fig. 2 leads to a $\sim 0.7\%$ reduction in R_{CZ} [32] and thus *restores* the agreement with helioseismology. The sound speed and density profiles which are presently underestimated in the region $0.2R_{\odot} \lesssim r \lesssim R_{CZ}$ would also be corrected by the opacity modification displayed in Fig. 2.

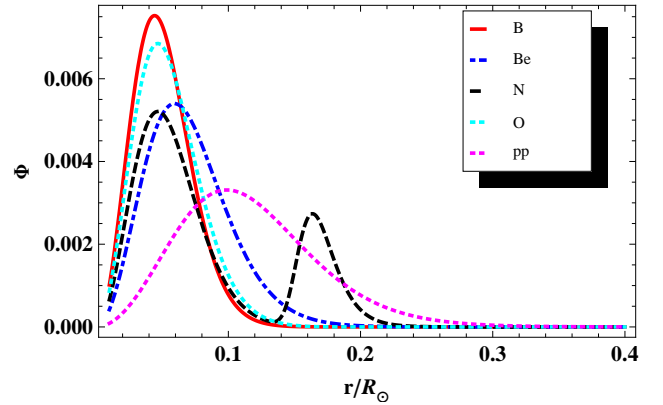


FIG. 3: Neutrino producing regions in the solar interior

The modification of the luminosity profile extends into the neutrino producing region as displayed for the SSM in Fig. 3. Comparing with Fig. 2 we see that precision measurements of different neutrino fluxes may be able to test the ADM model and determine its parameters. The ADM mass determines the scale height r_{χ} , hence the relative modifications of individual neutrino fluxes, while the cross-section determines the capture rate and thereby the overall modification. Both Monte Carlo simulations [31] and the ‘linear solar model’ [32] show that the variation of neutrino fluxes with respect to localised opacity changes in the neutrino producing region ($r \lesssim 0.2R_{\odot}$) scales approximately as $\delta\Phi_B \sim 1.5\delta\kappa$ and $\delta\Phi_{Be} \sim 0.7\delta\kappa$. The opacity variation in Fig. 2 leads to variations $\delta\Phi_B = -17\%$, $\delta\Phi_{Be} = -6.7\%$ and $\delta\Phi_N = -10\%$, $\delta\Phi_O = -14\%$ [32]. Measurements of the ^8B flux by Super-Kamiokande [33], SNO [34] and Borexino [35] are precise to 10% while the expectations vary by up to 20% depending on whether the old [25] or the new [27] composition is used [26]. For the ^7Be flux, the theoretical uncertainty is 10%, while Borexino aims to make a measurement precise to 3% [36]. SNO+ is expected to make a first measurement of the pep and CN-cycle fluxes [37]. Thus the effects of metallicity and luminosity variations can be distinguished in principle.

CONCLUSIONS

Asymmetric dark matter does not annihilate upon capture in the Sun and can therefore affect heat transport in the solar interior and consequently neutrino fluxes. This is particularly true for particles with self-interactions which would also explain the paucity of sub-galactic structure. We have shown that the presence of such particles in the Sun can solve the ‘solar composition problem’.

Intriguingly a 5 GeV ‘dark baryon’ would naturally a) have the required relic abundance if it has an initial asymmetry similar to that of baryons, b) have a self-interaction cross-section of the right order to explain sub-galactic structure, c) modify the deep interior of the Sun, restoring agreement between the standard solar model and helioseismology, and d) be consistent with recent hints of signals in direct detection experiments [17, 19]. Such a 5 GeV ADM particle would lower the solar neutrino fluxes which ought to be testable by the Borexino and (forthcoming) SNO+ experiments.

Note added: After this paper was submitted to arXiv (1003.4505), another study appeared [39] with similar findings concerning the effect of ADM on helioseismology and neutrino fluxes. However a second such study [40] finds negligible effects using a solar model simulation.

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